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NUMERICAL AND EXPERIMENTAL EVALUATION OF BLAST RETROFIT OF WINDOWS

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ABSTRACT

Retrofitting windows against blast load environments is a topic under considerable investigation. The retrofits added to existing buildings need the strength either to survive under the explosive loadings and/or to protect the building occupants. A retrofit method must prevent the glazing from entering the structure, while maintaining its structural integrity, before that retrofit method can be considered for installation within a facility. In order to provide design concepts for explosive testing, an iterative process was undertaken with finite element (FE) simulations for each retrofit design to develop retrofit details that meet the objectives of protection and structural integrity. Multiple variations of a particular retrofit can be simulated at a cost much less than required to test the variations. Three different retrofit methods were investigated in this study: a vertical blind system, a muntin frame anchored to vertical steel tubes, and a muntin frame anchored to a rigid reinforced concrete wall. An initial concept was developed for each case and a preliminary design done. Each concept was rigorously analyzed using FE simulations to determine the member sizes that were needed to resist the blast loading and prevent the penetration of glass fragments into the structure. Results from each simulation will be compared against experimental data to assess the finite element models. By performing a substantial number of simulations, several successful retrofit concepts were developed with a considerable cost savings over a purely experimental investigation.

INTRODUCTION

Current events have led to a need for buildings to provide adequate protection for their occupants to the effects of explosions that occur outside the structures. While this level of protection, higher than historically needed, can be designed into new buildings, it is also needed in existing structures. To that end retrofits are needed that can enhance the structural integrity of the existing structure. Often these retrofits need to be designed within stringent parameters, including existing space and without altering the architectural features of the building.

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This paper summarizes numerical and experimental efforts to develop window retrofit concepts for use by the U.S. Department of State. These retrofits will be used to mitigate the effects of an external detonation on the window systems within structures. Of utmost importance is protecting the occupants of the structures from the weapon effects and from debris caused by the detonation. Numerical analysis with finite element (FE) codes on high performance computing (HPC) systems has been incorporated into the design process of the retrofits. Once the retrofit systems discussed in this paper were developed, they were analyzed through the use of HPC codes and evaluated by experiments. If problems were found during the analysis phase, the designs were changed until they numerically survived under the desired loading conditions. The objective of the experiments – and ultimately the entire project - was to evaluate the hazard mitigation performance of window retrofit concepts.

Three retrofit systems are discussed in this paper. The combination of numerical and experimental analysis began in this project with the experimental failure of the initial test of the first system, a set of steel vertical blinds (shown in Figure 1). The failure was analyzed using finite element models, and potential redesigns were simulated to determine adequate parameters for the vertical blind system to survive. The finite element models were validated through the simulation of the original vertical blind system experimental failure. The simulation method used a combination of steel shell and solid elements to represent the sheets, tubes, and bolts that made up the majority of the parts of the retrofit systems. The same model types and modeling techniques were used in the design process for the two other retrofit designs, a muntin frame, i.e. a frame with cross members, supported by vertical tubes (pictured in Figure 2), and a basic muntin frame concept (shown in Figure 3). Multiple iterations were performed on each design to determine viable parameters that would survive the given threat level. Structural members were sized and characteristics determined through the numerical modeling and validated by the experiments.

Figure 1: Vertical blind retrofit system

Figure 2: Muntin frame with tubular supports

Figure 3: Simple muntin frame

FINITE ELEMENT OVERVIEW

Structures subjected to explosive detonation environments are frequently modeled with explicit finite element computer codes. These analyses usually provide analysis of the structural response of the system and insight into its behavior. Often simulations discover parts of the behavior that had not been previously anticipated. In this study simulations of the dynamic blast environment applied to the window system retrofits were performed using the finite element code PARADYN [Hoover, et. al., 1995], the parallel version of the explicit, large-deformation code DYNA3D [Whirley and Engelmann, 1993]. DYNA3D has many tools that were used to build the models of the window retrofit systems. These included the contact or sliding interfaces, an appropriate material model, and pressure boundary conditions. These features allowed the models to be built with the precision needed.

Sliding interfaces were used to model the contact between different parts of the models, as well as to tie two geometrically different parts of the model together. These interfaces either allowed contact, sliding, and separation between the nodes or rigidly fixed the nodes together depending on the interface type specified.

A "Rate-Dependent Tabular Isotropic Elastic-Plastic" (DYNA3D material model 24) was used to model the steel in each of the retrofit systems. Various strengths of steel were used. The density for all of these was set at 7.85 g/cm^3, while Poisson's ratio was defined as 0.3. Values for the yield strength, ultimate strength, failure strength, and plastic strain levels were generalized from standard handbooks rather than from actual experimental data. The steel strain rate enhancement curves were taken from PSADS [DSWA, 1998] Figure 4-49. This constitutive model allowed the plastic portion of the behavior to be explicitly specified by interpolating between stress-effective plastic strain pairs of data until the failure criteria was met. Once the effective plastic strain within an element exceeded the allowable effective plastic strain, the element failed and was removed from the simulation.

Smeared properties were used in an elastic-plastic material model (material model #3) to simulate the glazing used in the muntin frame models. The density was smeared from the various layers into a single shell layer that was the actual glazing thickness. The initial stiffness of the glazing was based on uncracked glass. While having the correct overall mass, the structural properties of this smeared window have not been validated. It was assumed that the glazing would survive under the loading and the use of the smeared properties and the elastic material model would not adversely affect the response of the retrofit systems. The important function of the modeled glazing here was to transfer the load into the frame, and the glazing shell elements were not allowed to fracture or fail. More detail about each retrofit and its numerical model will be discussed in the appropriate following section.

VERTICAL BLIND SYSTEM

As pictured in Figure 1, this retrofit system consists of vertical strips of 20 gage steel that are anchored to the floor and ceiling via a steel connection. The critical part of this design was this connection (an example connection is shown in Figure 4). It had to allow for movement in the through-the-blind direction, absorb some of the energy put into the system, and still hold the blind in place throughout its response. The original connection failed when subjected to the blast environment. A slotted bolt that connected the steel sheet to the C-section was subjected to excessive bending which led to failure, and the blind was torn away from the connection. Finite element (FE) models were then used to reproduce this failure and aid in the redesign of the connection to ensure the retrofit's survival. After iterating through many different types of designs, two were chosen to be used in the follow-on experiment. More detail about this particular retrofit system can be found in O'Daniel and Dinan, 2001.

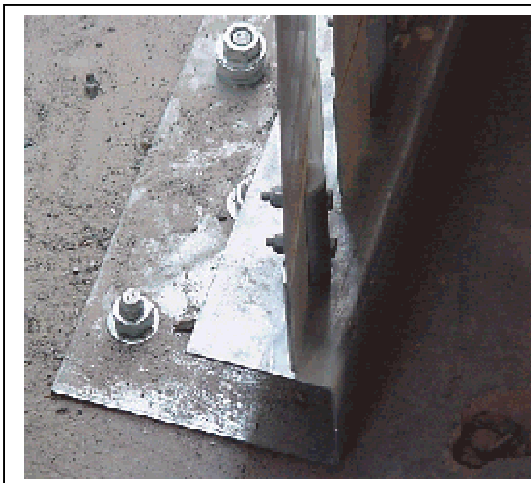

Figure 4: Vertical blind connection

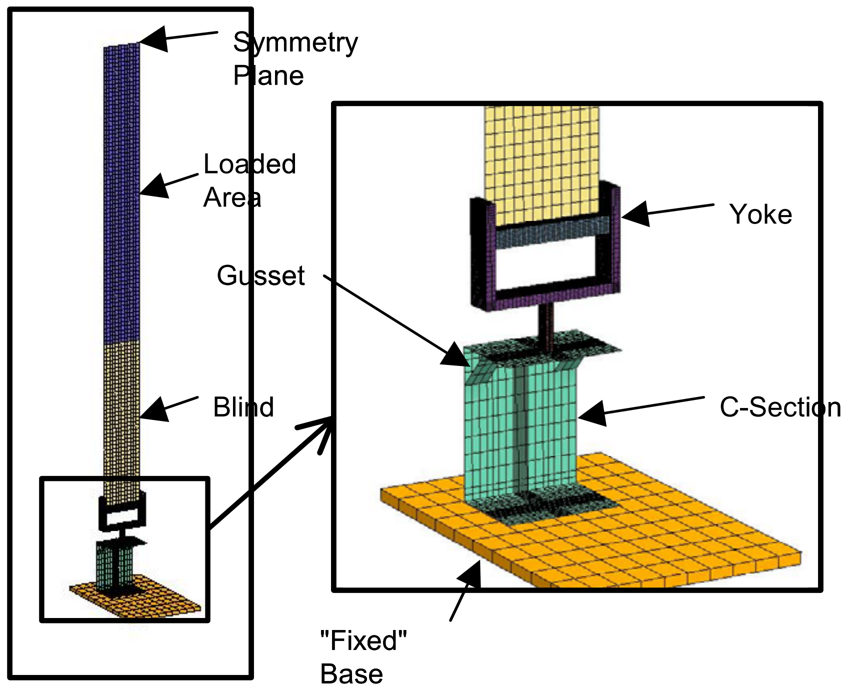

Figure 5: Finite element model of the vertical blind system

A description of one of the FE models of a single vertical blind can be seen in Figure 5. Only a single blind was modeled so as to conservatively estimate the strength of the entire system. If a single blind would survive the loading, the entire system would also survive. A symmetry plane was used at the top of the model seen in Figure 5 since the floor and ceiling connections were identical. In this particular model, the blind sheet is attached to a yoke part, which is then bolted to a steel C-section. The various parts of the model were numerically tied together using the sliding interfaces described above. Shell elements were used to model the blind itself and the C-section. The yoke, support bolt, and the floor were comprised of solid elements.

Loads were applied to only the part of the blind that was exposed in the window frame (approximately the top 2/3 of the steel blind sheet). These loads consisted of a combination of pressure loading that represented the blast pressure and an imposed initial velocity and added mass to represent the glazing striking the blind. These values were determined from the initial response of the window as calculated by HAZL [ERDC,2001], an engineering-level window response computer code. As can be seen in Figure 6 (this figure depicts a solid connection type, the second chosen for follow-on testing), the C-section partially unfolds under the loading. Closeup views of the deformed connections can be seen in Figure 7. While exhibiting some plastic strain in various parts of the connection, both types numerically and experimentally survived the desired loading environment. Two views of the posttest vertical blind system can be seen in Figure 8. Although the vertical blind system survived structurally, the concept did not work as planned. The large amount of deformation seen by the vertical blinds allowed glazing debris to penetrate into the room.

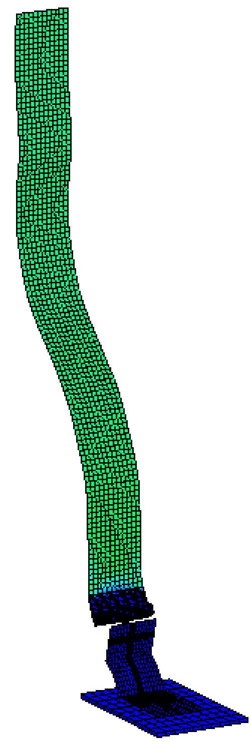

Figure 6: Deformed vertical blind finite element model

MUNTIN FRAME WITH VERTICAL TUBES

A muntin frame retrofit system (Figure 2) was developed next. The major aspects of the design were set, consisting of the steel tube frame and cross sections, and the larger vertical steel tubes for support. Of interest was determining if the bolts were sized correctly between the frame and the vertical tubes, as well as those that attached the tubes to the floor and ceiling. Also to be determined numerically was the thickness of each of the tubes, ensuring that the members did not fail. This was particularly important for the cross members of the muntin frame.

All of the steel members of the FE model of the muntin frame with vertical tubes system (shown in Figure 9) were modeled with shell elements. The glazing was also modeled using shell elements and did not allow for failure, as described in the Finite Element Overview section. The bolts were modeled using spot-weld interfaces that initially tied two nodes together, and then allowed “failure” or separation when failure criteria were met. Failure was allowed when a combination of shear and normal forces between the two nodes exceeded prescribed values. A sliding interface between the window glazing and the front of the frame allowed the blast pressure - a pressure boundary condition on the front of the glazing – to be transmitted into the frame and its support system. Sizes were determined for both the bolts and the tube thicknesses, and the system was tested. A partial failure is allowed by the muntin frame system since the glazing system pulls out of the edges of the frame and is held from projecting into the room behind by the cross members. While the glazing fails, flying debris is avoided and the blast pressures allowed through are lowered to acceptable levels.

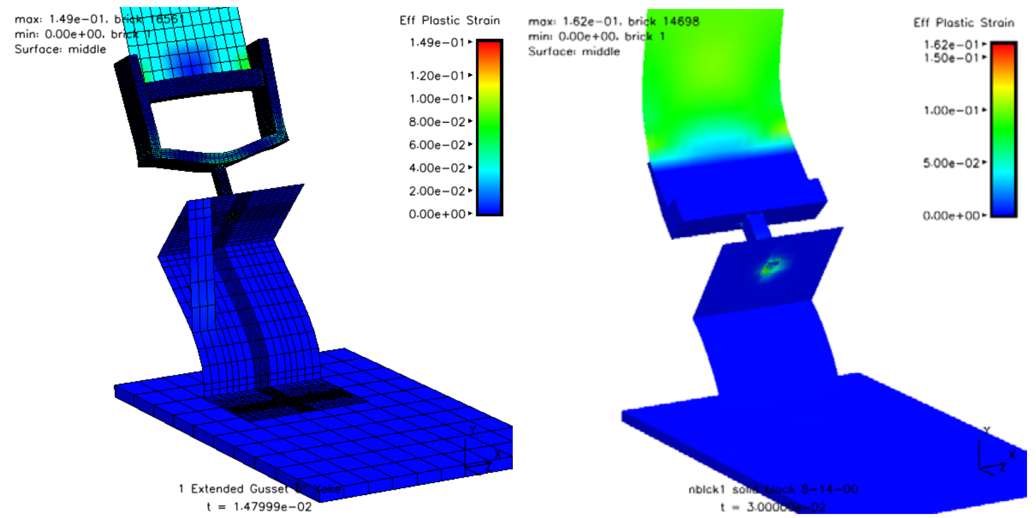

Figure 7: Final two connection designs for the vertical blind system

Figure 8: Posttest views of the vertical blind system and the connections

Both the numerical and experimental systems deformed in a similar response mode, as can be seen in Figures 10 and 11. There was approximately 50% more deflection in the predicted simulation frame than was measured in the test, but higher strength steel was used in the experiment. The connections survived with little deformation and the bolts behaved as predicted by the FE model. A satisfactory design was developed through the modeling process and validated by the experiment.

MUNTIN FRAME

The muntin frame (Figure 3) was very similar to the previous window retrofit system described above, but the frame was anchored into a steel frame that was directly connected to a concrete wall rather than supported by vertical steel tubes. The dimensions of this muntin frame were modified to replicate a particular window size of interest. Half-inch bolts were used to anchor the muntin frame to the surrounding steel frame.

An initial FE simulation (shown in Figure 12) used the half-inch bolts and had a thickness of 0.25” for all the tubular steel members. As can be seen in Figure 13, some tearing occurred, exhibited by the failed shell elements in the center of the cross section. Similar tearing was seen where the cross members were attached to the frame. The window elements have been artificially removed from these figures so the response of the frame can be clearly seen.

The test produced very similar results as the simulation for this muntin frame. This can be seen in the various parts of Figure 14, which shows the deformed shape and some of the steel tearing of the cross members. Included in this figure is a side view of the deformation of the cross members, a close-up of the tearing of the cross member at the top of the frame, and a view

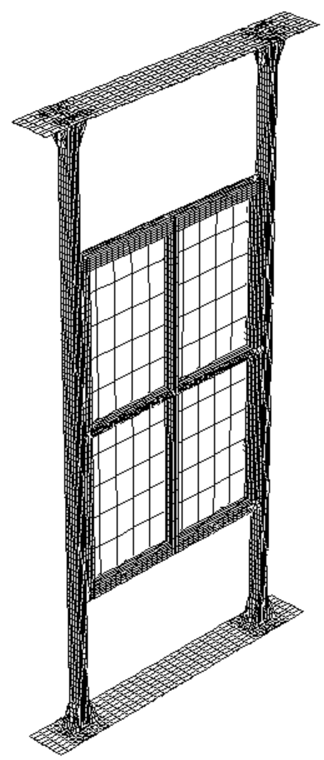

Figure 9: Finite element model of muntin frame with tubular supports

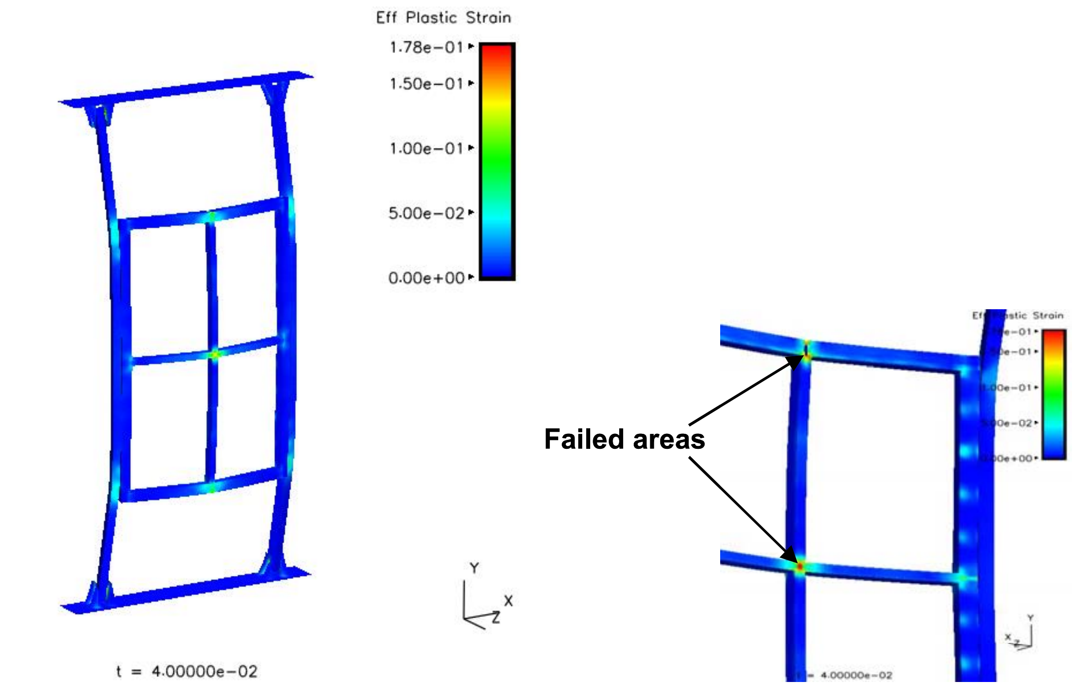

Figure 10: Deformed muntin frame with tubular supports finite element model


Figure 11: Posttest muntin frame with tubular supports system

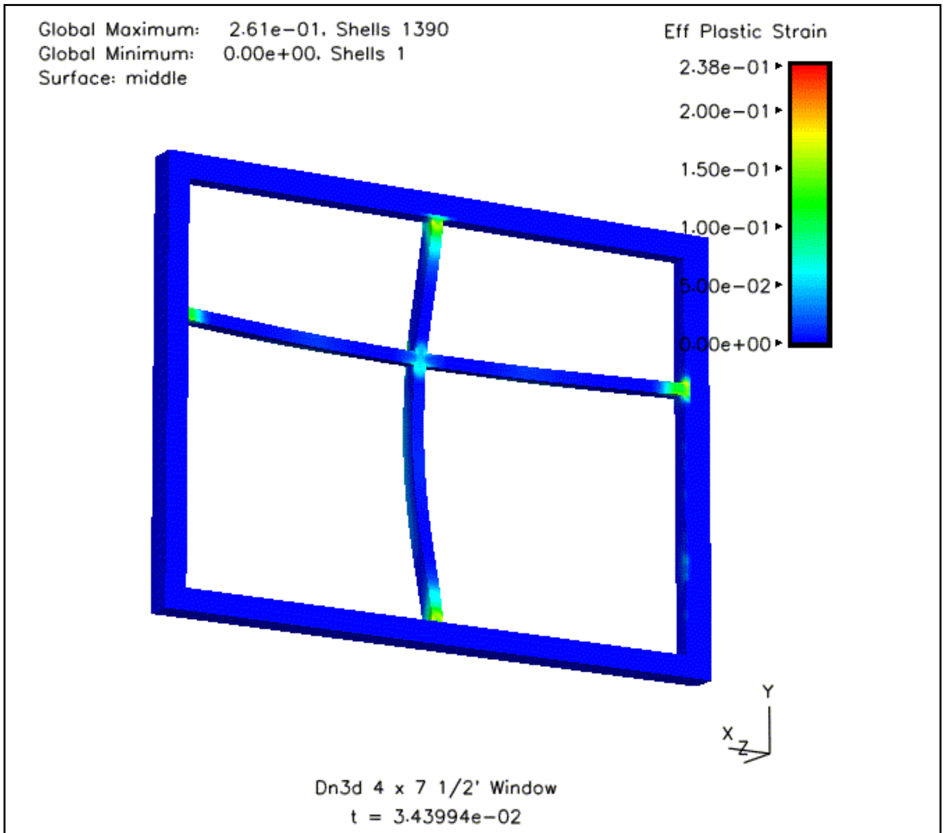

Figure 12: Muntin frame deformed shape

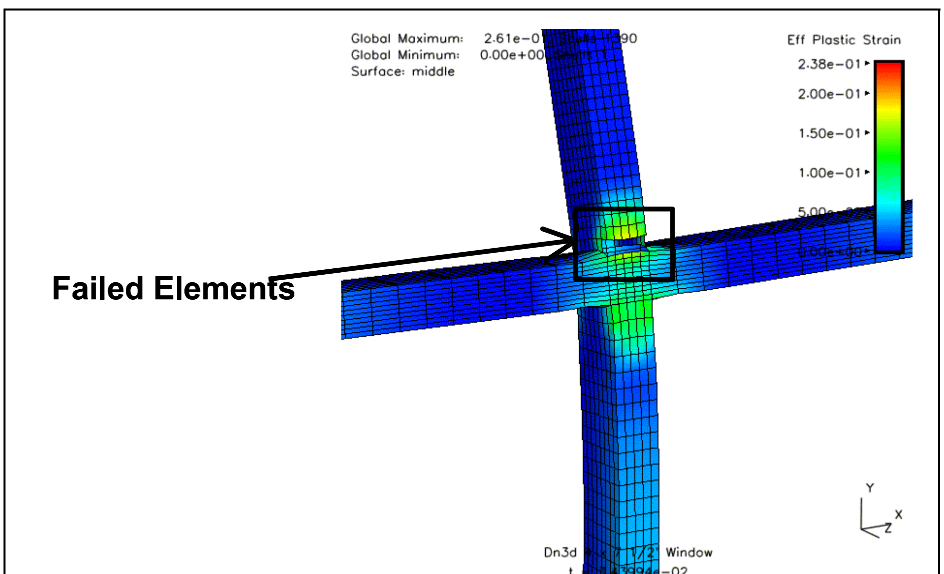

Figure 13: Tearing of cross members of muntin frame system

Figure 14: Various views of the posttest muntin frame

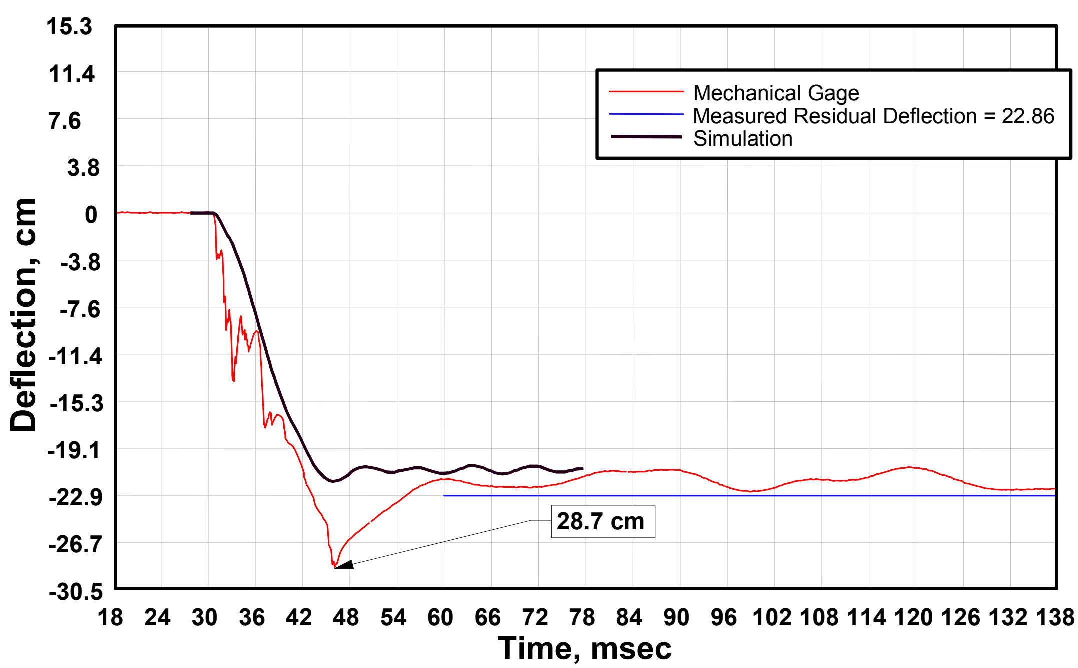

Figure 15: Deflection of the center of the cross members

of the frame deformation at its bottom. Figure 15 shows a comparison of the deflection of the center of the cross members. While the peak deflection was higher in the experiment than the simulation, the final deflection of the system was approximately 1.78 cm further in the experiment than the FE model.

SUMMARY

A higher level of protection was achieved with two of three retrofit systems. The combination of numerical and experimental methods was used to design and evaluate window retrofit systems to mitigate the effects of an external detonation. Three different systems were developed and successfully tested as a part of a larger retrofit program. The initial problem with the vertical blind system was successfully reproduced numerically. The redesigned system survived the desired loading conditions, the concept was flawed and the blinds did not stop window shards from entering the structure after an external detonation. The muntin systems performed very well under the desired loading conditions Members and bolts were sized for both the muntin frame with vertical tubes and the basic muntin frame that allowed the systems to survive the experimental blast load environment. There was extremely good correlation between the experimental and numerical data for the basic muntin frame. Developing the retrofit systems through simulation and testing proved to be successful and allowed the two muntin frame systems to be deemed as viable retrofits to protect personnel.

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REFERENCES

Defense Special Weapons Agency, 1998. "Technical Manual Design and Analysis of Hardened Structures to Conventional Weapons Effects." DSWA DAHSCWEMAN-97, Alexandria, VA.

ERDC, “Window Fragment Hazard Level Analysis, the HAZL Model,” U.S. Army ERDC, Vicksburg, MS, October, 2001.

Hoover, C.G., DeGroot, A.J., and Pocassini, R.J., 1995. "Paradyn: DYNA3D for massively parallel computers," USRL 53838-94, Livermore, CA,.

O’Daniel, J.L., and Dinan, R.J., 2001. “Use of Finite Element Simulations to Improve the Design of a Window Retrofit,” Proceedings of the 10th International Symposium on the Interaction of the Effects of Munitions with Structures, San Diego, CA.

Whirley, R.G., and Engelmann, B.E., 1993. "DYNA3D-A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics-User Manual," UCRL-MA-107254, Rev. 1.